Performance of the MEDLI Integrated Sensor Plug (MISP) Hardware and TPS Response Reconstruction

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Session 2: Mars Science Laboratory

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Outline

- Overview of MEDLI and MISP
- MISP thermocouple flight data
- Timing of turbulent transition
- Bondline temperature response
- Un-margined TPS thickness for as-flown trajectory
- Conclusions

Overview of MEDLI

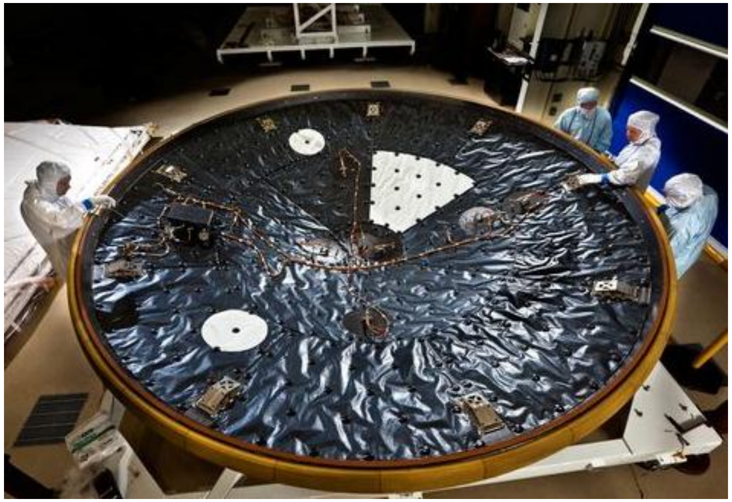
- Mars Science Laboratory (MSL) had a 4.5m diameter tiled PICA instrumented heatshield

- The heatshield was instrumented with the MSL Entry Descent and Landing Instrumentation (MEDLI) suite, with three main components:
  - **MISP (MEDLI Integrated Sensor Plug),** in-depth sensors at 7 locations embedded in the TPS
  - MEADS (Mars Entry Atmospheric Data System), pressure ports and transducers at 7 locations
  - Solid State Electronics (SSE) box for data collection from MISP and MEADS

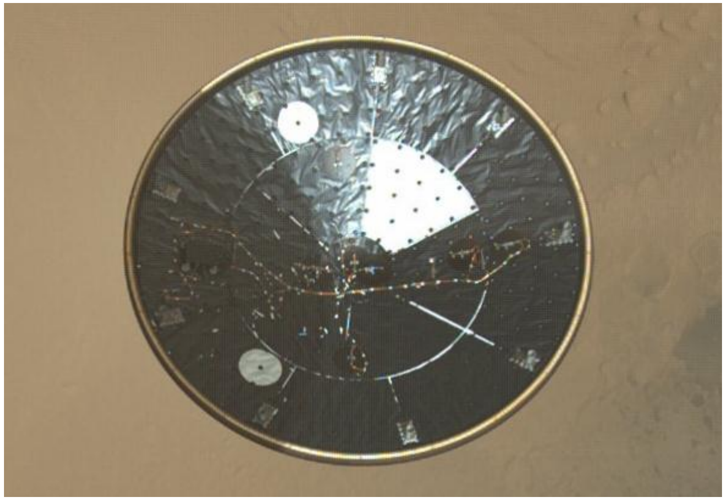
- MEDLI data was stored during entry and telemetered after landing

- All MEDLI data was successfully received, and MEADS data (presentation by Mark Schoenenberger) used to reconstruct the trajectory

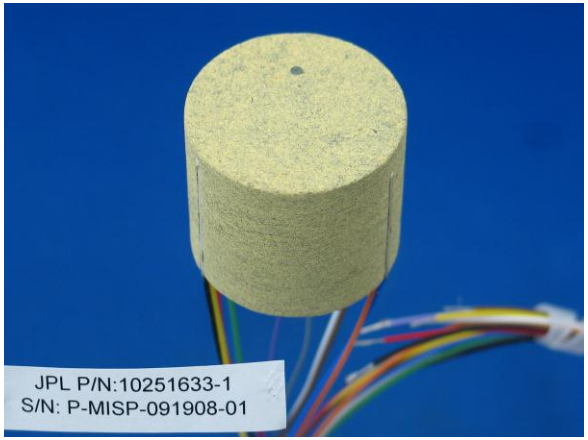
Underside of MSL heatshield



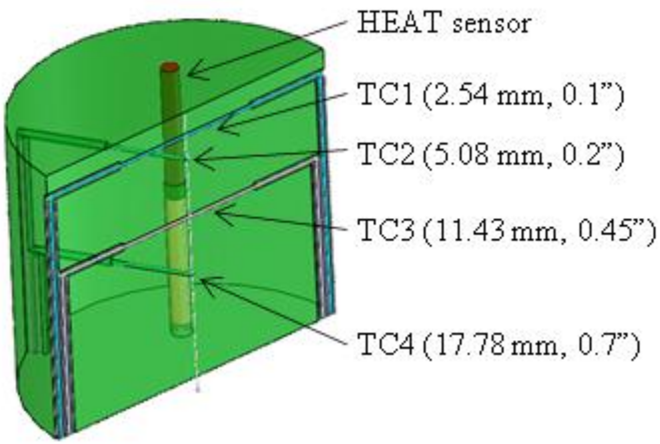
MEDLI and Heatshield – at MARS!



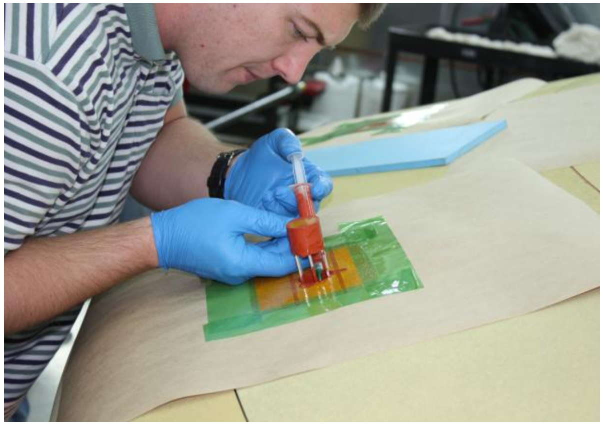
MEDLI Integrated Sensor Plug (MISP)



MISP before installation



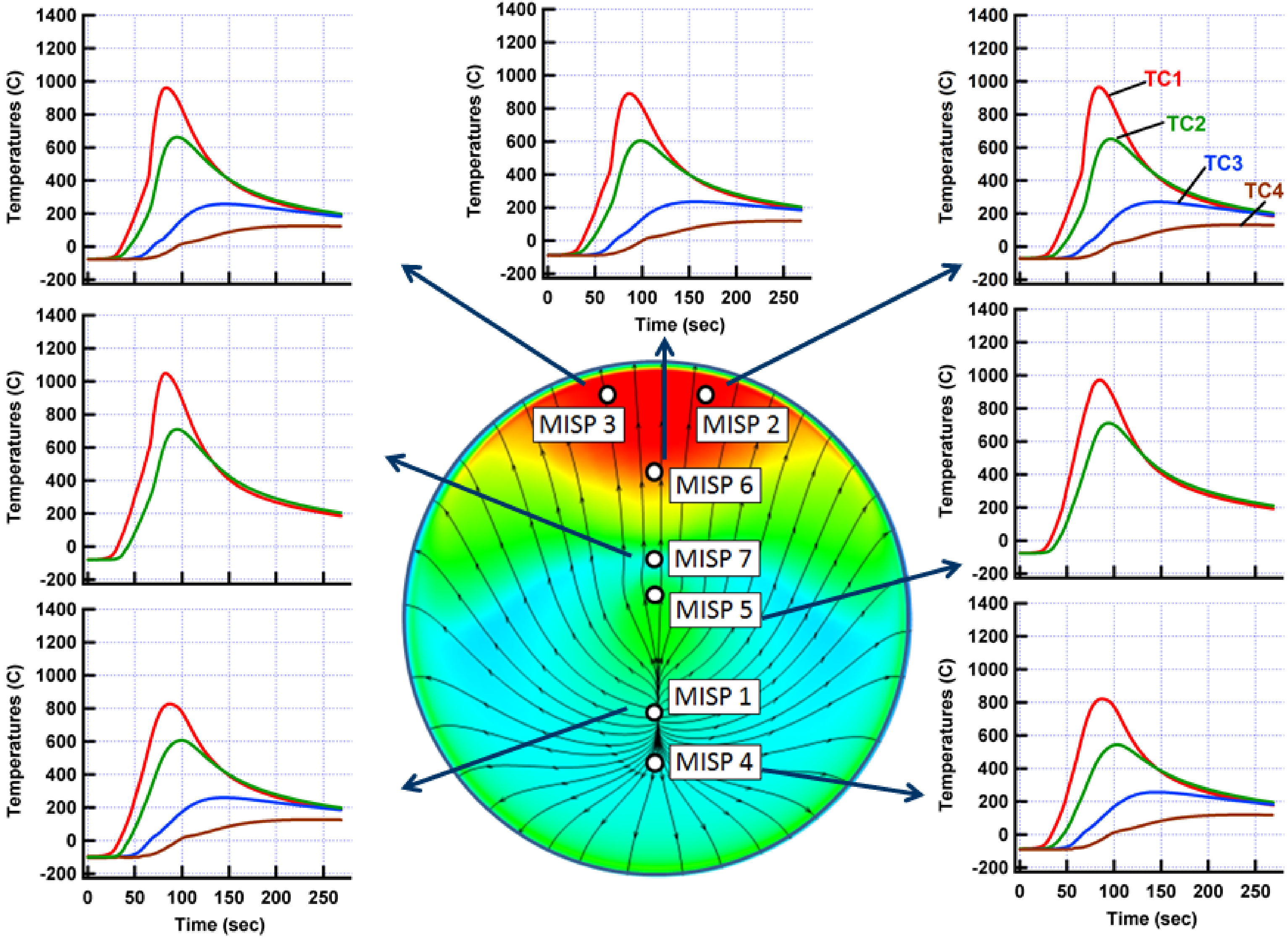
MISP cross section



MISP3 being installed

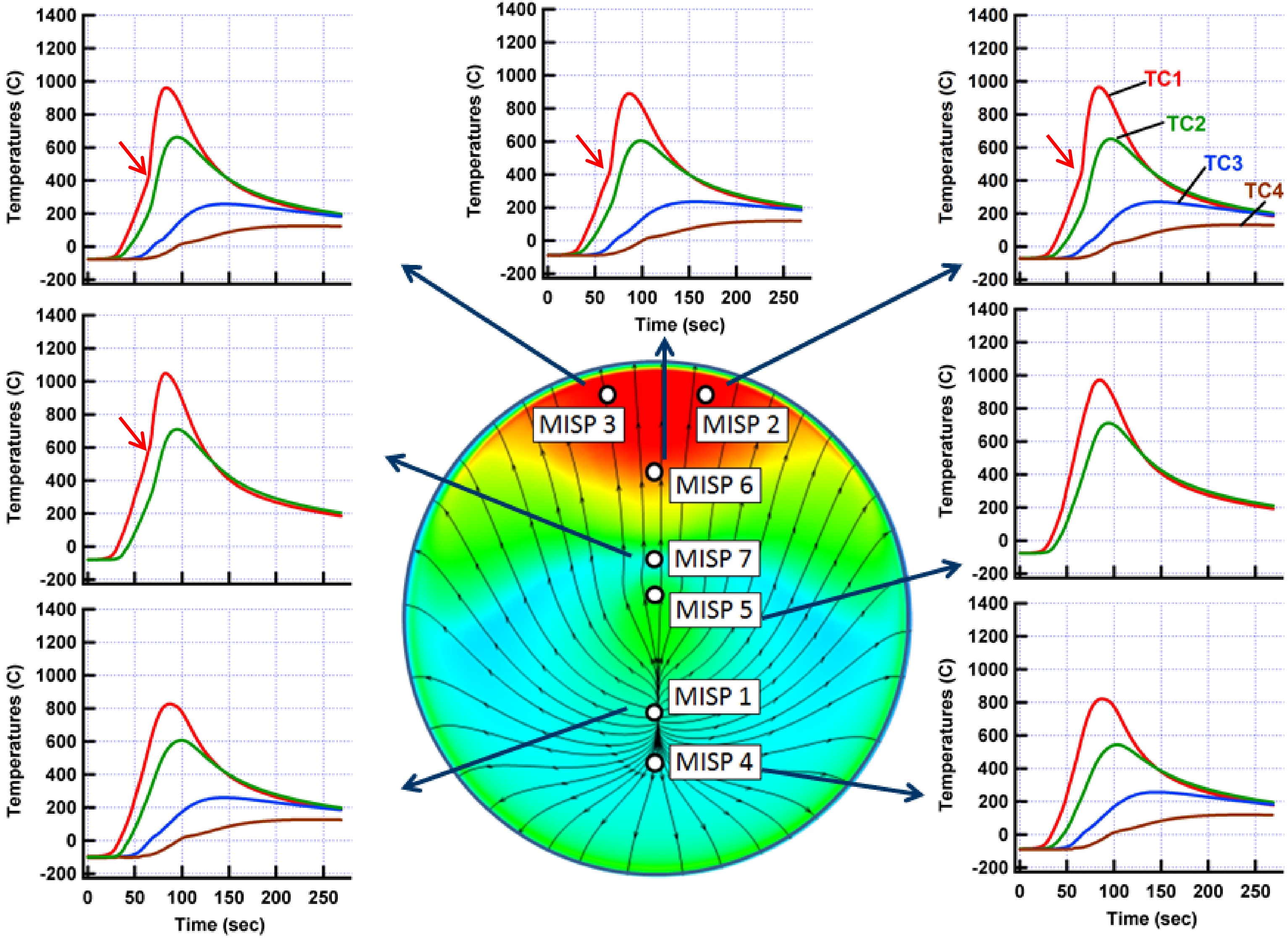
- Each plug was 1.3” diameter by 1.14” long PICA cylinder, and contained:
  - **Four Type-K thermocouples (TCs) with range of -170 – 1030 ^{o}C**
  - One HEAT (Hollow aErothermal Ablation and Temperature) sensor designed to track ablation process through the thickness
- TCs were built according to ASTM standards (E377-08) for low-conductivity materials
- TCs closest to the surface were sampled at 8 Hz, and deeper TCs were sampled at 1 – 2 Hz
- The four TCs are installed at depths of 0.1”, 0.2”, 0.45”, and 0.7” from the top surface

MISP Flight Thermocouple Data



- All thermocouples returned data successfully
- All near surface thermocouples survived the heat pulse → TPS recession < 0.1 inch

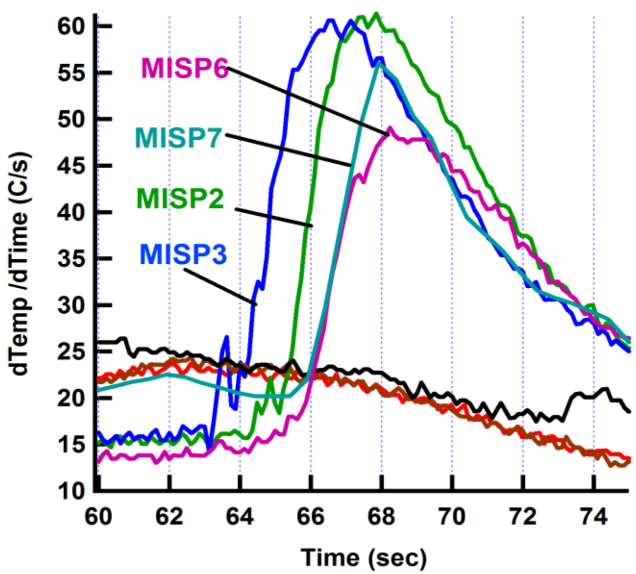
MISP Flight Thermocouple Data

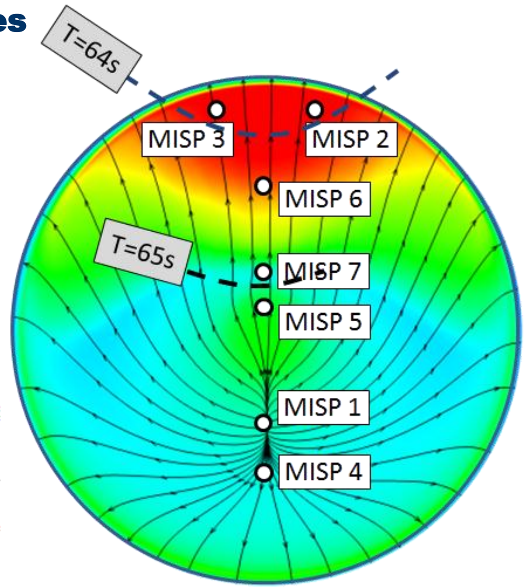


- Boundary layer transition to turbulence observed as sudden temperature slope changes on the leeside

Turbulent transition on MSL heatshield

Time derivative of temperatures



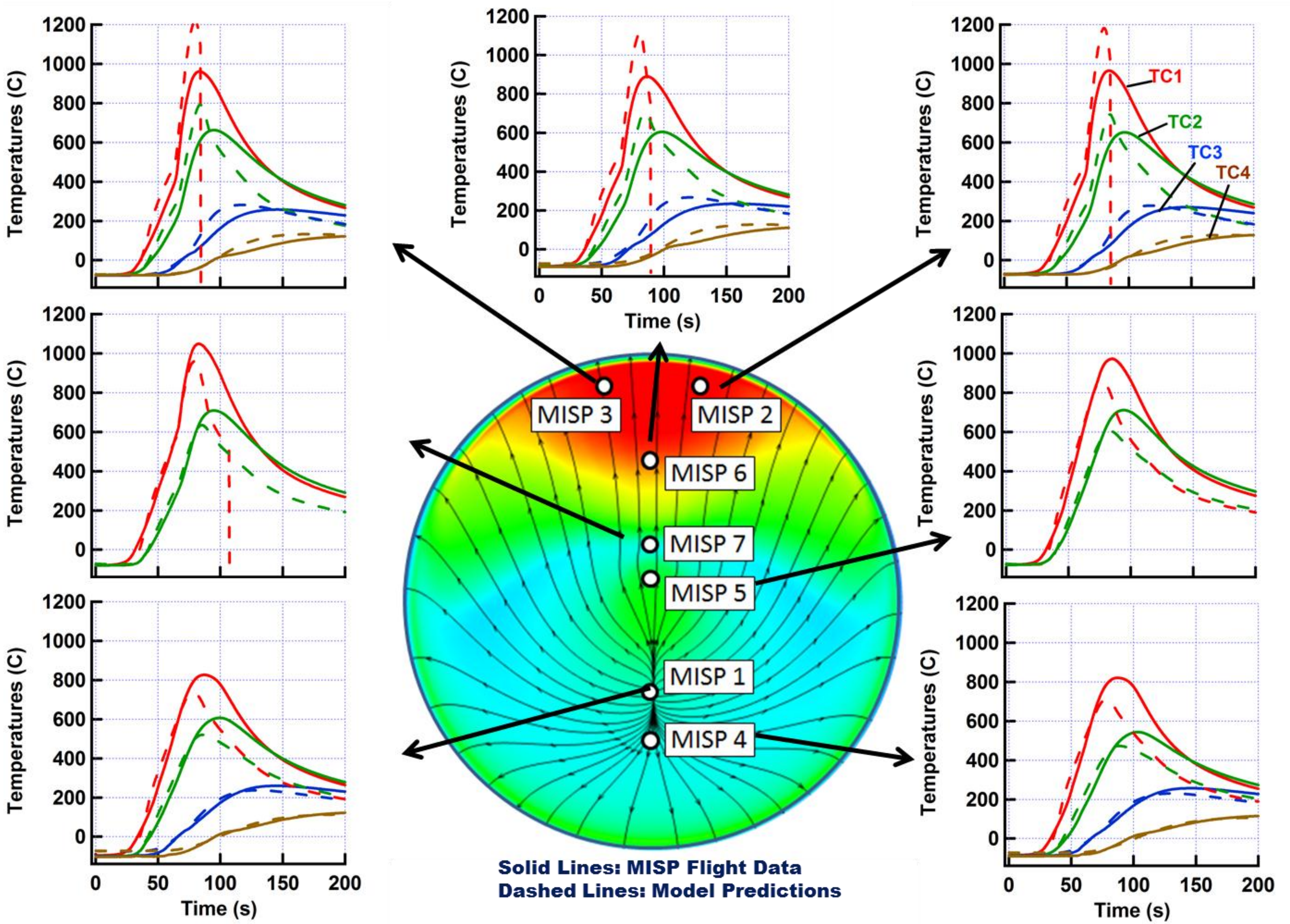


Boundary layer transition times

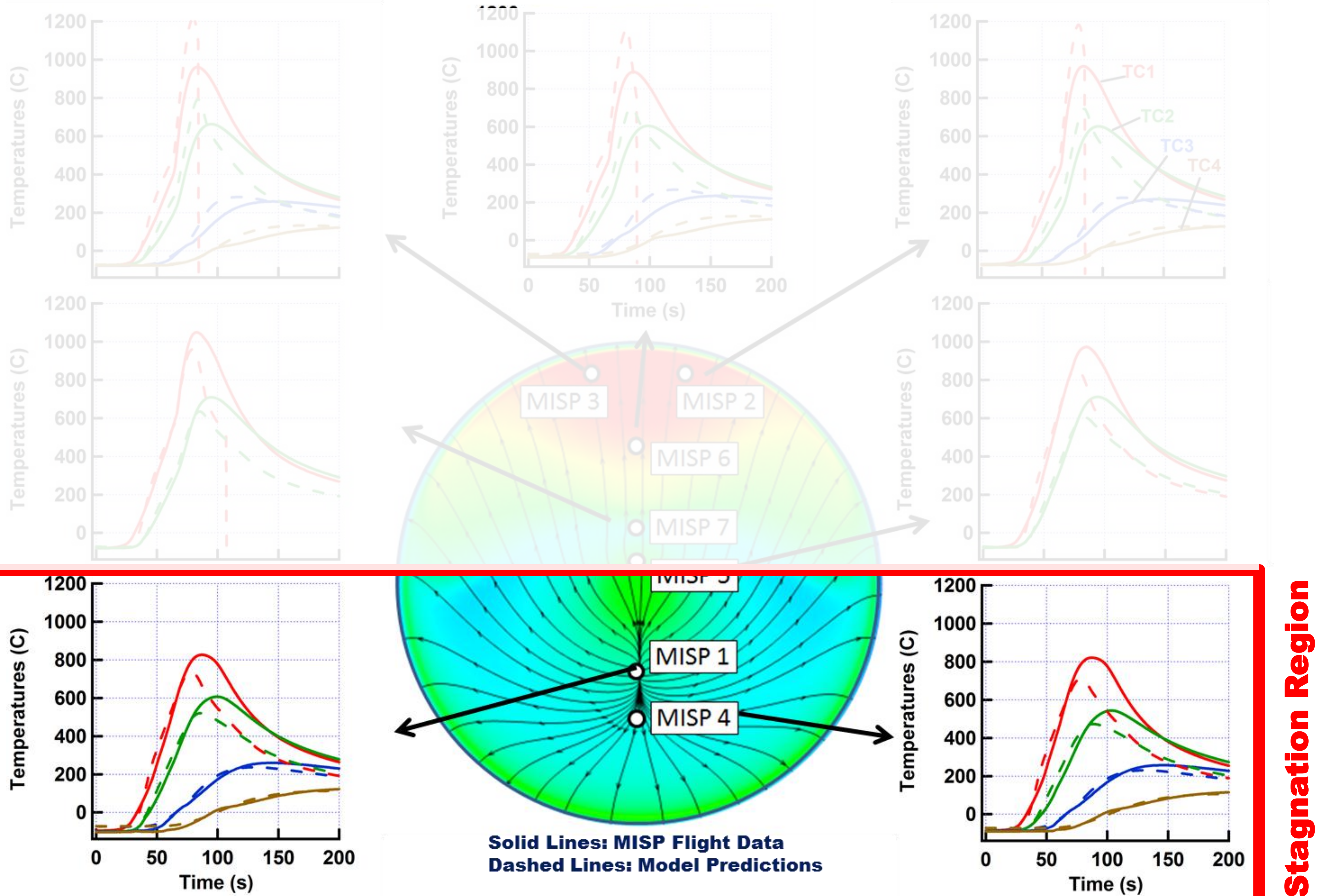
Plug	Flight	Re_θ=200	Re_{kk}=190 *(k = 2 mm)*
MISP3	63	52	62
MISP2	64	52	62
MISP6	65	57	63
MISP7	65	71	65
MISP5	73	None	62

- Boundary layer momentum thickness Reynolds number (Re_θ) criterion can’t describe speed of transition front
- Roughness-based Reynolds number (Re_{kk}) criterion promising
  - We surveyed available roughness criteria for CO_2
  - Roughness heights of 2 mm were consistent with tile gaps and trips around MISP
  - 2 mm roughness height does job of predicting transition time
- We postulate a series of tile gaps and MISP trips acted together as a distributed roughness
  - *See upcoming AIAA papers for more details*

Model predictions compared to flight data



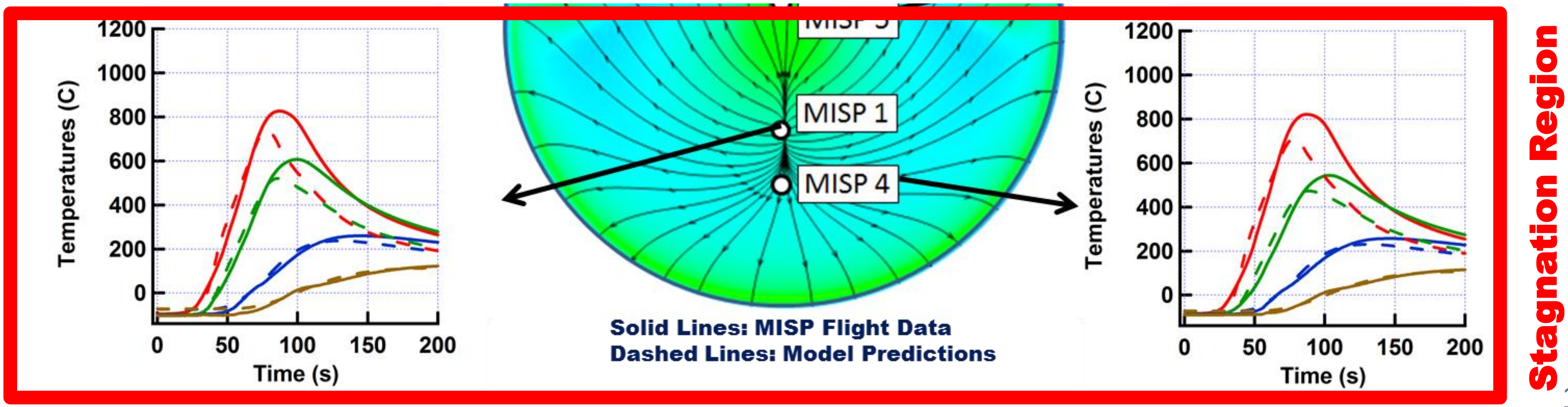
Stagnation region



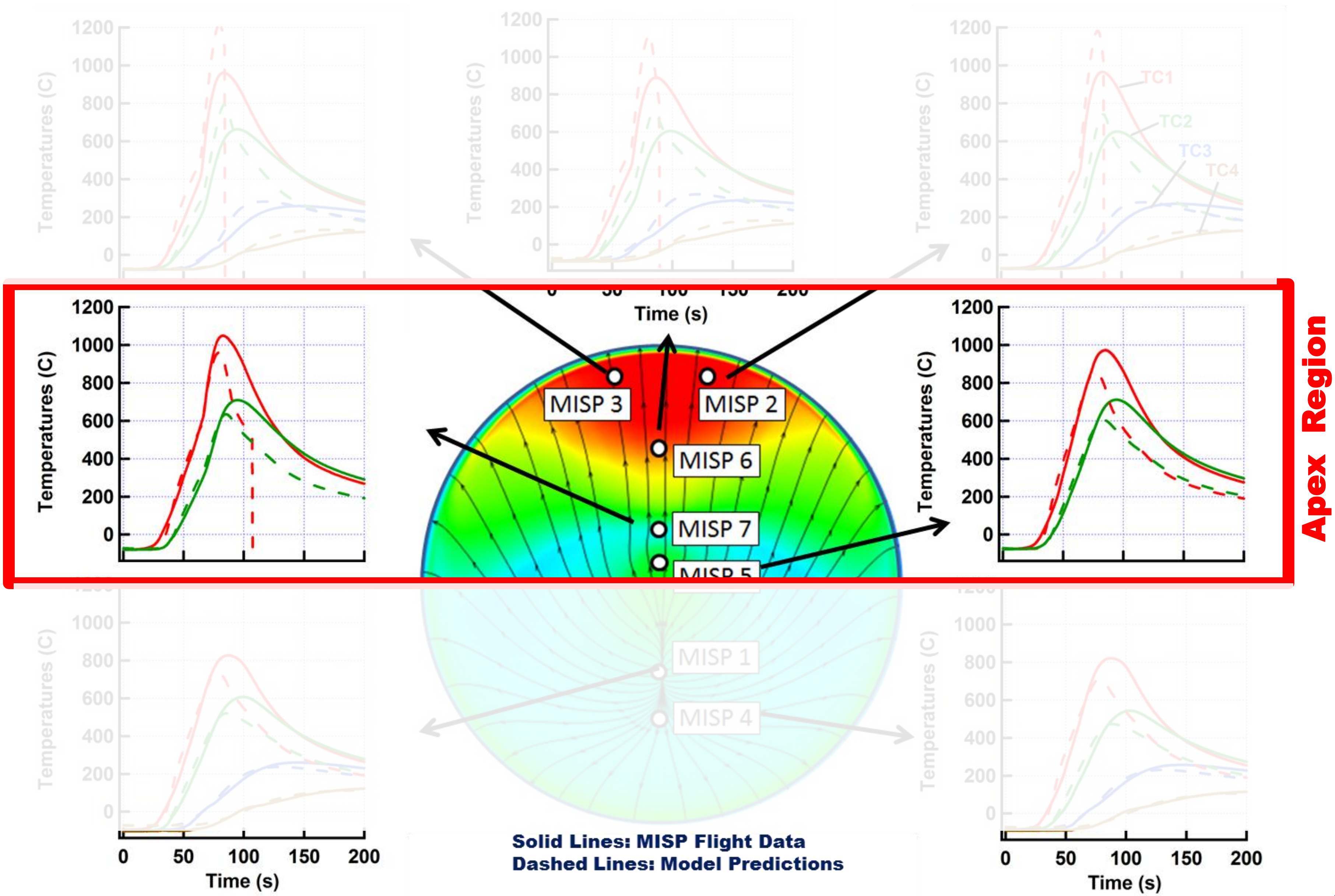
Stagnation region

- Peak temperatures and cool-down in stagnation region are under predicted
- Deeper temperatures are predicted well

- Possible causes of higher temperatures
  - Radiative heating
  - Some flow disturbance due to pyrolysis gas injection or roughness possible
  - PICA char material property



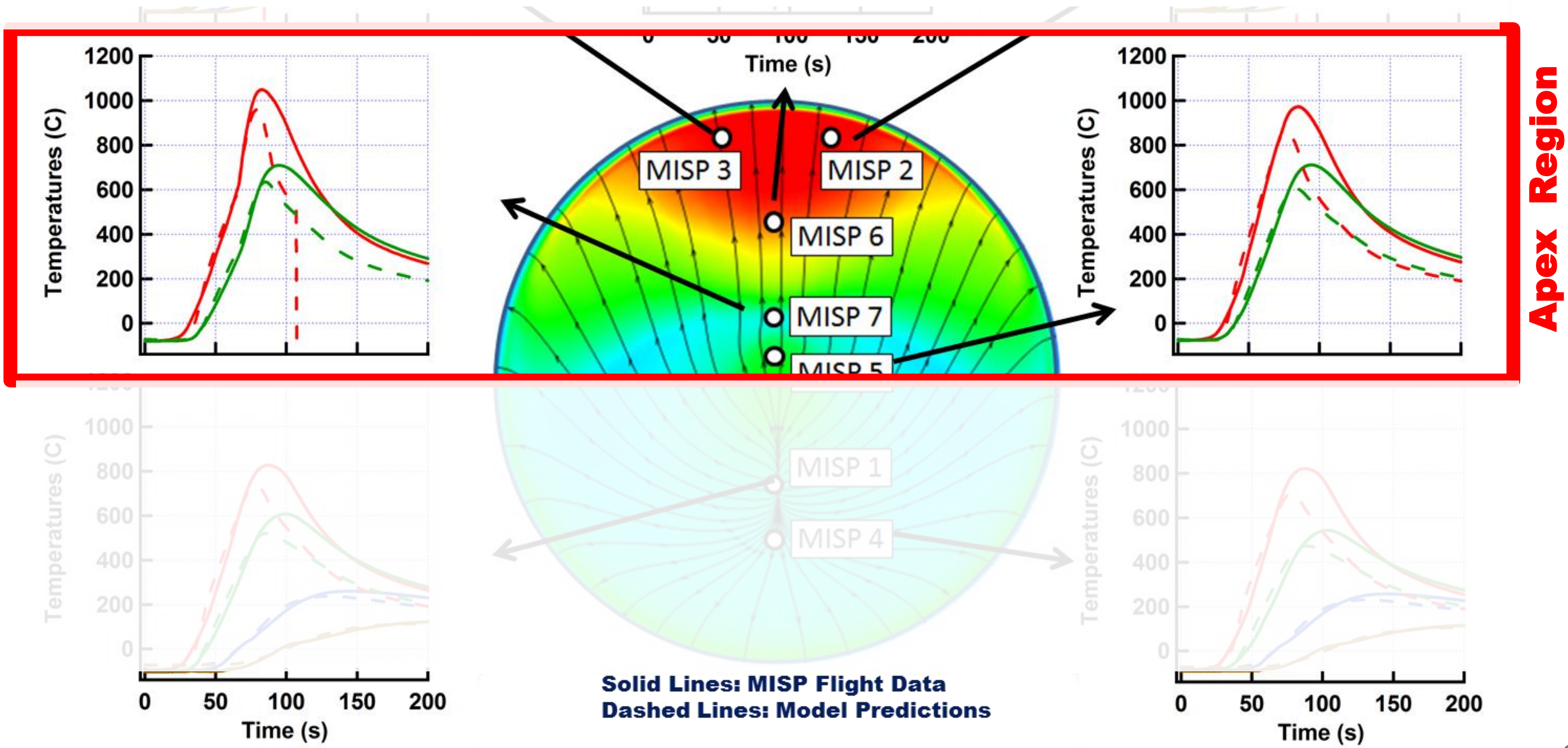
Apex region



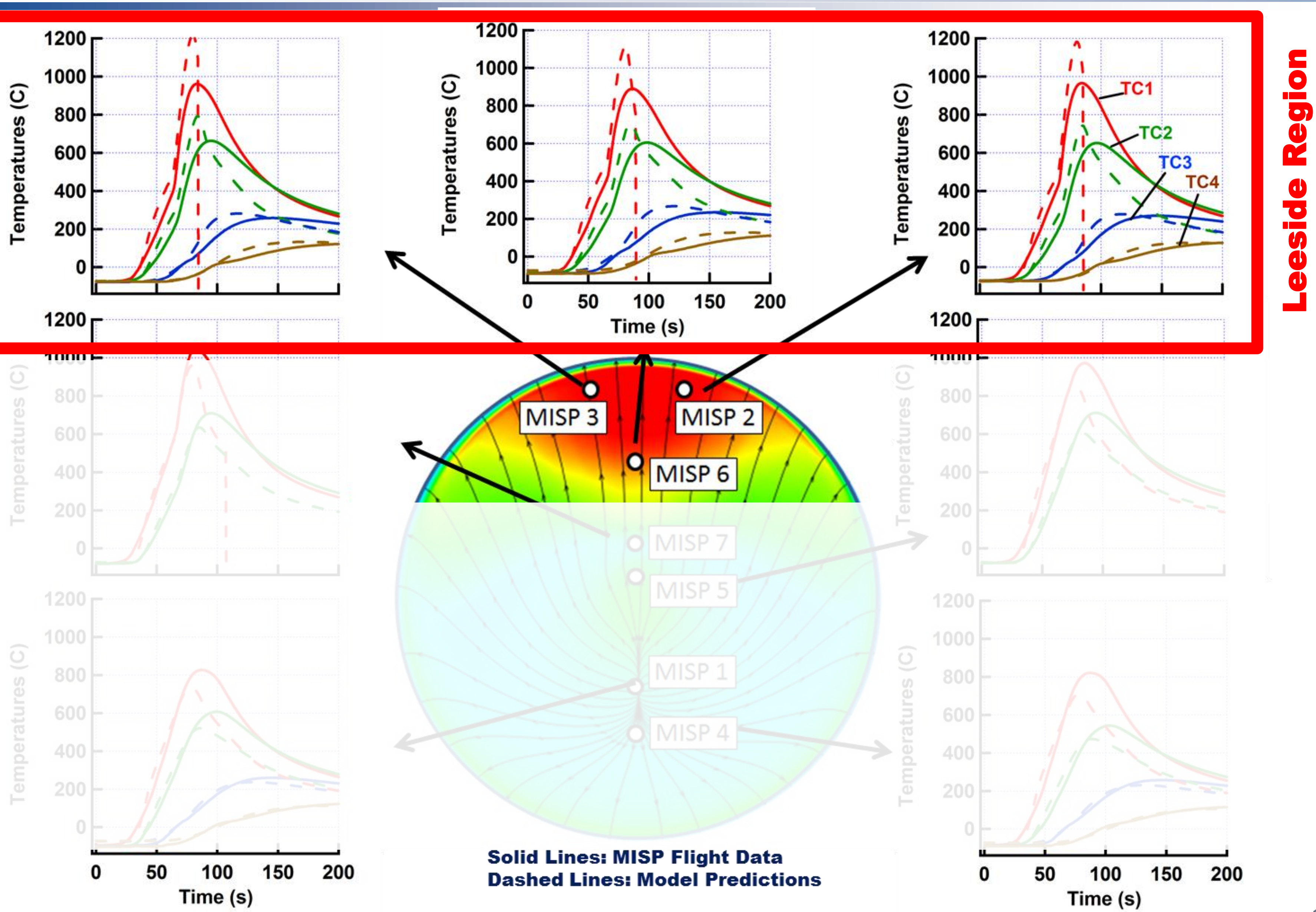
Temperatures (C)
Time (s)
MISP 3
MISP 2
MISP 6
MISP 7
MISP 5
MISP 1
MISP 4
TC1
TC2
TC3
TC4
Apex Region
Solid Lines: MISP Flight Data
Dashed Lines: Model Predictions

Apex region

- Peak temperatures in apex region are also under predicted
- Possible causes of higher temperatures in addition to causes discussed for stagnation region
  - Roughness induced flow disturbance

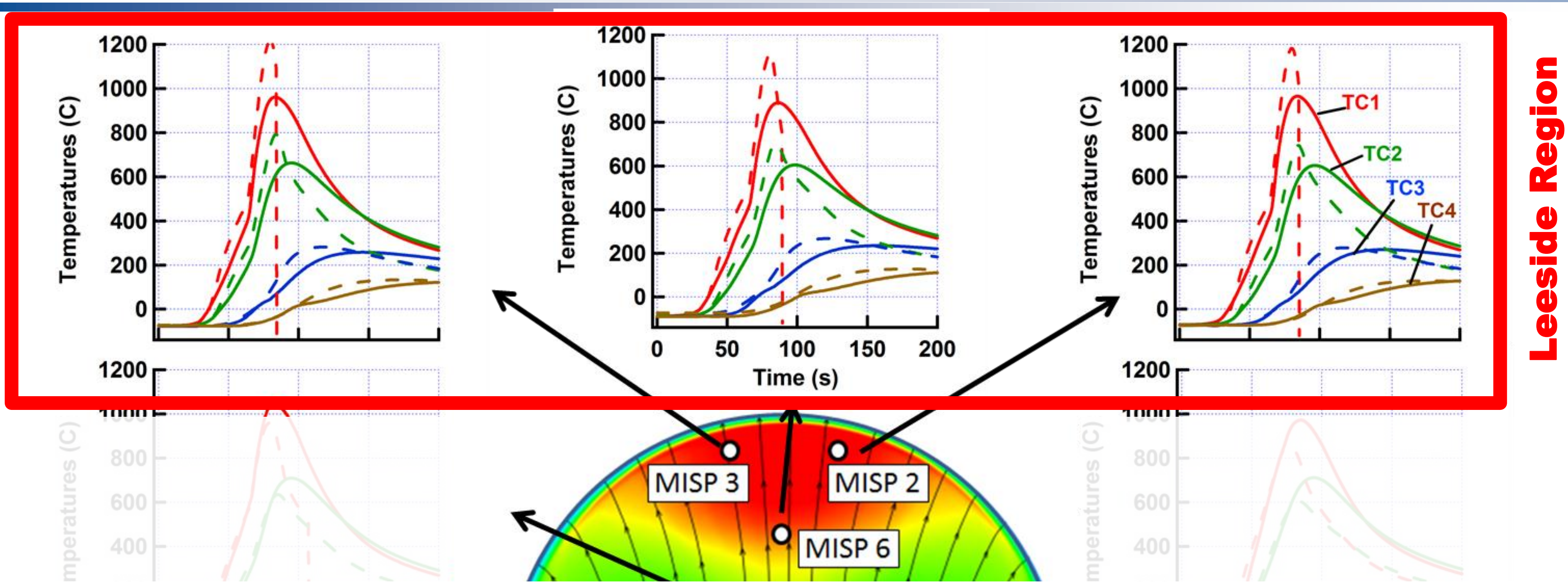


Leeside region



Solid Lines: MISP Flight Data
Dashed Lines: Model Predictions

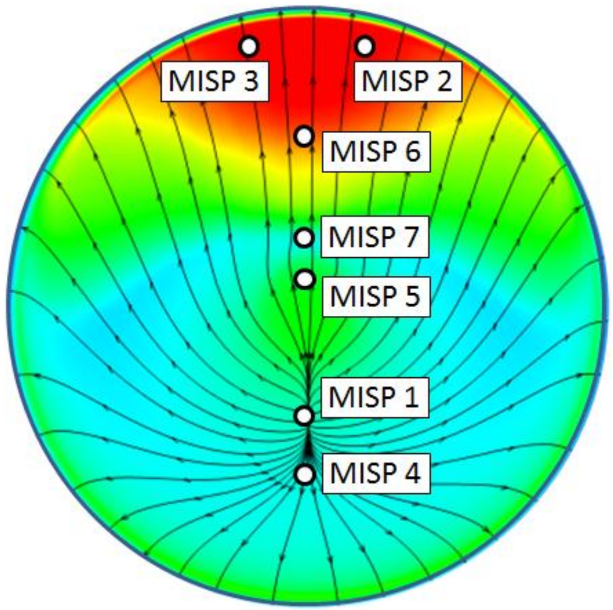
Leeside region

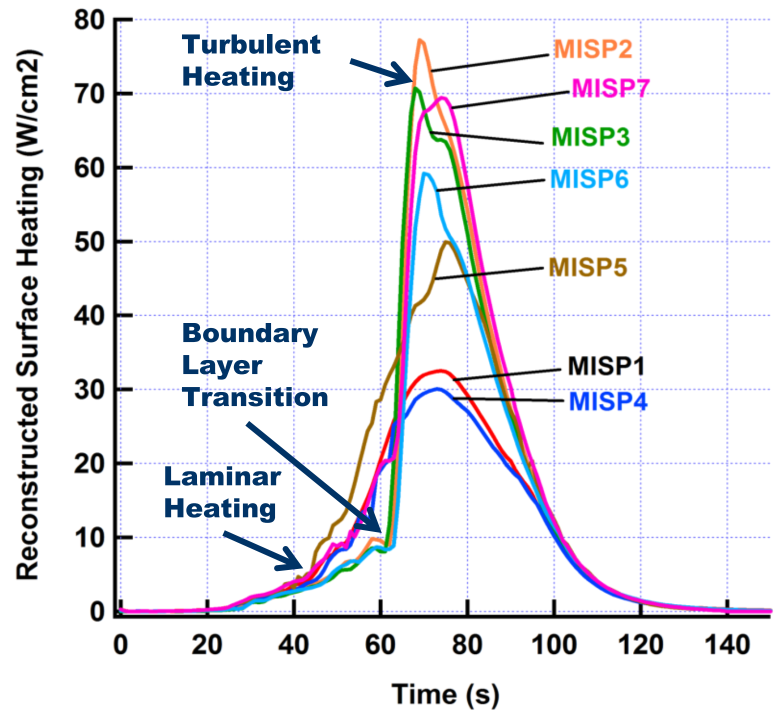


- Peak temperatures in leeside region are over-predicted

- Possible causes
  - Recession is over-predicted
  - Possible deficiency of turbulence model
  - Other causes discussed before

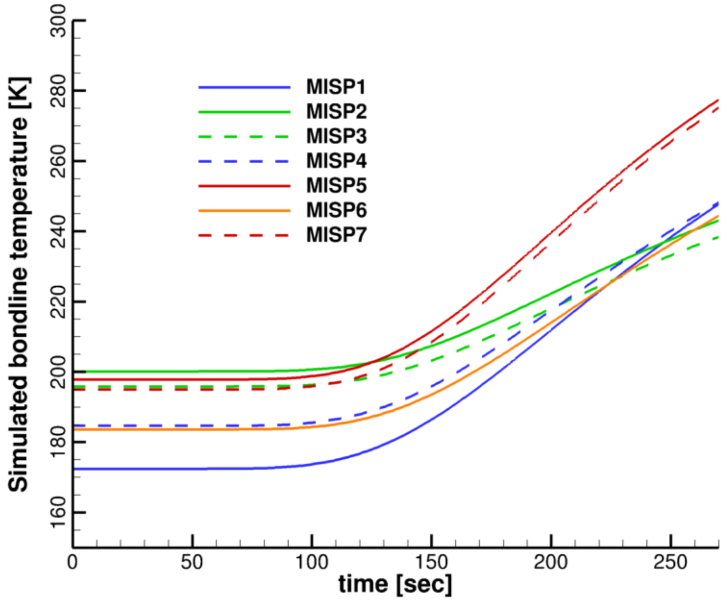
Aerothermal reconstruction





- We can use the shallowest thermocouple (TC1) to estimate the surface heating
  - See poster by Milad Mahzari for more details. The reconstructed heating is sensitive to recession material model
  - Requires an inverse reconstruction performed using the material response code
- Due to several modeling differences, the reconstructed heating isn't directly comparable with design CFD heat rates, but trends are still discernable
- We can use deeper thermocouples to understand the bondline TPS response

Bondline temperature response



Plug	Peak $T_{bondline}$	$T_{bondline}$ Rise
	K	*K*
MISP1	247	75
MISP2	243	43
MISP3	238	43
MISP4	248	64
MISP5	277	80
MISP6	244	61
MISP7	275	80

- We can predict the TPS bondline temperature rise using the deepest TC at each plug
- Bondline temperature response depends strongly on initial temperature and substructure materials
- MISP5 & MISP7 probably reached the highest temperature
  - The aluminum honeycomb substructure density in MISP5 &MISP7 is about half that of the MISP2 and MISP3

- In design the TPS thickness is picked so that $T_{bondline}$ stays below limit of 523 K (250 ^{o}C) prior to heatshield jettison (268 seconds)
  - Predicted peak well below design limit
  - How can we use MISP data to improve our design process?

Determining un-margined TPS thickness

- To determine the minimum amount of TPS, we run material simulations anchored with flight TC data
  - We use TC2 data because some TC3 data didn't exceed the design temperature limit
  - We size TPS so that the bondline temperature stays below 250 ^{o}C at each plug
- MISP3 needs the thinnest TPS, at 11.4 mm, because of its dense heat-absorbing substructure.
- MISP5 and MISP7 would have had the thickest TPS required
- The greatest un-margined thickness at MISP locations for the as-flown trajectory is at **15.7 mm**
- To compare with the as-built thickness (31.8 mm) we must repeat the MSL margins process at the MISP locations

Location	Thickness mm	Thickness *in*
MISP1	14.6	0.57
MISP2	11.6	0.46
MISP3	11.4	0.45
MISP4	13.2	0.52
MISP5	15.7	0.62
MISP6	13.6	0.53
MISP7	15.7	0.62

- MSL margins procedure included:
  - Trajectory variations (+3σ)
  - Aerothermal uncertainties (+3σ)
  - Material variability and model uncertainties (+3σ)
  - Manufacturing tolerances and considerations
- The successful landing of Curiosity and the data from MISP shows the MSL heatshield was conservatively sized

Conclusions

- All MISP thermocouples returned data successfully!
- All near surface thermocouples survived the heat pulse, indicating TPS recession was less than 0.1 inch everywhere—lower than we expected
- MISP TCs indicated boundary layer transition on the leeside
- The speed of the transition front cannot be explained by smooth wall transition
- Roughness-induced transition would explain speed of transition
  - Roughness trips may have developed due RTV swelling at gap fillers and around MISP instrumentation
- Design aerothermal and material response models tend to under-predict the near surface TC response, but over-predict (conservative) at deeper TCs
- Based on the MISP data, we've determined the un-margined TPS thickness on the as-flown trajectory
  - Ongoing work will revisit the MSL TPS sizing and margins process using the MEDLI data

Acknowledgements

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Questions?

Backup

Abstract

NASA's Mars Science Laboratory (MSL) entered the atmosphere of Mars on August 5th, 2012 and landed the 900 kg Curiosity rover. MSL represented a significant advancement in planetary entry, descent, and landing capability; with an entry mass of 3200 kg and a 4.5 m diameter heatshield, MSL was the heaviest and the largest Mars entry vehicle. The MSL heatshield was instrumented to acquire important flight data for aerodynamics, aerothermodynamics, and thermal protection system response. The instrumentation suite that captured this data was the Mars Science Laboratory Entry, Descent, and Landing Instrumentation (MEDLI),

The MEDLI suite consisted of 7 pressure transducers, 24 thermocouples, and 6 ablation sensors. It successfully acquired and returned surface pressure, in-depth temperatures, and material decomposition characteristics at various locations on the heatshield. The MEDLI suite on MSL represents the most extensively instrumented Mars entry heatshield. This submission presents an assessment of the thermal data received from the MEDLI Instrumented Sensor Plug (MISP), including some comparisons of in-depth temperatures with model predictions, and provides estimates of the aerothermal environment using the flight data.

What if we suppress recession?